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THESIS

SET-UP UNDER A NATURAL WAVE

by

Bruce J. Morris

March, 1997

Thesis Advisor:

E. B. Thornton

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SET-UP UNDER A NATURAL WAVE

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Submitted in partial fulfillment
of the requirements for the degree of

**MASTER OF SCIENCE IN METEOROLOGY AND
PHYSICAL OCEANOGRAPHY**

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ABSTRACT

Field measurements from a cross-shore array of two pressure sensors to measure waves and eight manometer tubes to measure mean water elevation are used to examine set-down/up across the surf zone. The manometer tubes are connected to differential pressure transducers onshore allowing continuous set-down/up measurements. Flume measurements of set-down/up are also examined. Measured values are compared with numeric set-up values incorporating roller theory describing wave breaking. The model has two free parameters, B representing the vertical fraction of the wave covered by the roller and ψ a scaling parameter for wave steepness. Optimal values of both are chosen by model fitting. Inclusion of the surface roller improves the set-up model fit to both beach and flume measurements.

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I. INTRODUCTION

As shoaling waves approach the shoreline, they increase in height, eventually become unstable, and break within the surf zone. The resulting change in wave-induced momentum flux through the surf zone is balanced by hydrostatic pressure forces associated with changes in the mean water level (MWL). This mean water level variation consists of a gradual depression of the mean sea level beginning offshore, where energy dissipation is negligible and momentum increases, reaching a maximum at the breaker line. Inside the surf zone there is an increase of the mean sea level, where significant dissipation occurs and momentum decreases, reaching a minimum at the beach face. The mean sea level depression is termed set-down and the increase is called set-up.

The theory of set-up/down was first explained by Longuet-Higgins and Stewart (1962), who showed that the changes in the momentum flux of the waves due to challenge and then wave breaking is balanced by a change in the mean water level. They introduced the term radiation stress to describe the excess momentum flux of the waves.

Laboratory measurements of set-up/down were demonstrated by Bowen et al (1968) using monochromatic waves. Using a simple description of wave breaking, $H_b = \gamma h$, where H_b is the

height of the breaker, γ is an adjustable coefficient and h is the local water depth, they over predicted set-down. Svendsen (1984) incorporated the concept of a surface roller to describe wave breaking to improve set-up prediction. He compared monochromatic lab measurements finding good agreement.

Field measurements of set-up maxima at the shoreline were made by Guza and Thornton (1981) utilizing a resistance wire run-up meter to determine the mean position of the swash oscillation on the beach face. They found $\bar{\eta}_{\max} \approx 0.17 H_s$, where H_s is the deep water significant wave height. Nielson (1988) used manometer tubes located at various distances in the cross-shore to measure changes in MWL relative to an offshore manometer well outside the surf zone. A major advantage of a manometer array is that it avoids having to precisely survey the vertical position of pressure sensors in the surf zone. Connecting the array onshore to glass tubes and a common reservoir, he photographed the glass tube meniscus level to obtain set-up values. King et al (1990) buried Paro-scientific pressure transducers in the sand to make continuous measurements of set-up throughout the cross-shore.

The objective of this paper is to compare set-up/down numerical model values with observed values acquired at a near-planar beach during the Monterey Beach Experiment

(Monterey, California, 1996) and from LIP 11D Delta Flume Laboratory Experiments (Amsterdam, Netherlands, 1993). Improvement in numerical model set-up values is examined by incorporating surface roller theory. Also, a new field measurement system to acquire continuous set-up data in the field composed of manometer tubes connected to differential pressure transducers was tested and is described.

II. THEORY

In the past, field measurements of set-up have been acquired using pressure sensors on the bottom either buried or elevated above the bed. The dissonant conditions of the surf zone makes accurate surveying of the vertical positions of the pressure sensors extremely difficult. Another, often overlooked, problem with elevated pressure sensors is that the oscillating motion of the water about the sensor introduces error in the pressure readings associated with the Bernoulli effect. The Bernoulli equation for time varying flow is described by:

$$p = \frac{\rho}{2} (\bar{u})^2 + \rho g z + \frac{\partial \phi}{\partial t} \quad (1)$$

where ρ is the density of the fluid, u is the horizontal velocity, and ϕ is a velocity potential associated with the waves. The Bernoulli term, $\frac{\rho}{2} (\bar{u})^2$, leads to a positive bias error since it is a velocity squared contribution. The bias is avoided by either burying the sensor or, in the case of the flume, mounting the pressure sensor flush to the wall so that the impinging velocity component is zero. In the measurements described herein, the pressure sensors are either flush or buried in the bottom.

In the model for solving set-up/down, the energy balance equation is used first to solve for wave energy and surface roller terms, which are then used to describe the wave momentum flux. Assuming steady state conditions, straight and parallel contours and incorporating a surface roller (Lippmann and Thornton, 1997),

$$\frac{\partial}{\partial x} (E_w C_g \cos \alpha) + \frac{\partial}{\partial x} (E_r C \cos \alpha) = -(\varepsilon_r) \quad (2)$$

where the wave energy, $E_w = \frac{1}{8} \rho g H_{rms}^2$, E_r is the energy in the roller, ε_r is the roller energy dissipation, C_g the group velocity, C is the wave speed and α the incident wave angle. The first term on the l.h.s. describes the energy input into the roller, and is defined by the cross-shore transformation of wave heights. The next term defines the shoreward advection of roller energy.

Wave set-up/down is described using the cross-shore momentum balance. Again assuming steady state conditions with straight and parallel contours, (Longuet-Higgins and Stewart, 1962),

$$\frac{\partial S_{xx}}{\partial x} = -\rho g (\bar{\eta} + h) \frac{\partial \bar{\eta}}{\partial x} \quad (3)$$

where S_{xx} is the momentum flux associated with the waves

radiation stress, the subscript xx signifies the onshore directed momentum is advected in the cross-shore direction, h is the still-water depth, and $\bar{\eta}$ is the time averaged difference between the still-water level and the mean water level in the presence of waves. The still-water level is defined as the water surface level with no waves present. Equation (3) states that changes in the incoming momentum flux are balanced by a hydrostatic pressure gradient force. These changes in the mean water level are set-down and set-up.

S_{xx} represents the excess momentum due to unsteady flow, and can be partitioned into two parts,

$$S_{xx} = \tilde{S}_{xx} + S'_{xx} \quad (4)$$

with \tilde{S}_{xx} representing the contribution by the wave motion and S'_{xx} the contribution by the wave roller. Momentum flux due to the wave motion to second order is (Phillips 1977),

$$\tilde{S}_{xx} = \int_{-\eta}^{\eta} (\rho \bar{u}^2 + p) dz \quad (5)$$

Substituting linear wave theory,

$$\tilde{S}_{xx} = \left\langle \left[E_w \frac{C_g}{C} \cos^2 \alpha + \frac{E_w}{2} \left(2 \frac{C_g}{C} - 1 \right) \right] \right\rangle \quad (6)$$

Equation (6) can be simplified for small incident wave angles in the shallow water,

$$\tilde{S}_{xx} = \frac{3}{2} E_w \quad (7)$$

An additional stress occurs when the waves break and is conceptually described by a surface roller. The surface roller is a volume of rotating fluid carried along at the wave speed. A stress is required to maintain the roller on the surface described by,

$$S'_{xx} = \frac{\rho A C^2}{L} \quad (8)$$

where L is the shallow water wave length. The area of the roller (Figure 1) is described using the hydraulic jump analogy from Lippmann and Thornton (1997),

$$A = \frac{(BH)^3}{4h \tan \sigma} \quad (9)$$

where B is the vertical fraction of the wave face covered by the roller and H is the height of the hydraulic jump taken here as the wave height. The area of the roller is inversely

proportional to slope of the wave face, $\tan \sigma$, a variable not well constrained by measurements. Thus it is assumed $\tan \sigma$ is proportional to the wave steepness described by,

$$\tan \sigma = \psi \frac{H}{L} \quad (10)$$

where ψ is a constant of proportionality. The free parameters B and ψ are adjusted to give the best fit between the measured data and the numerical output of the energy balance equation.

The use of a roller in the energy flux balance allows for delay in the conversion of organized wave motion to dissipation during wave breaking. In turn, the momentum change is delayed in the nearshore, affecting the slope of the mean water surface (set-up).

Input to solve set-up in equation (3), is obtained from the energy balance equation (2) using a forward stepping numerical scheme. The energy balance equation is used to determine both H_{rms} and the area of the roller. The momentum flux terms (6) and (8) are then combined in a centered finite difference scheme to provide set-down and set-up values. The model is initialized at the offshore boundary, well outside the surf zone, where an initial value $H_{\text{rms}0}$ is given and $\bar{\eta}$ is set to zero.

III. EXPERIMENT

A. MONTEREY BAY FIELD EXPERIMENT

Wave and mean water level data were acquired as part of the Monterey Bay Experiment held at the Del Monte Beach in Monterey, California during November and December 1996. Mean water levels were measured using an array of nine manometer tubes (m1-m9) of varying length deployed in a cross-shore array from ~4.2 m depth to the shoreline. Surface elevations were measured with a cross-shore array of seven pressure sensors (p1-p7) co-located with the nine manometer tubes (Figure 2). Data are described during the day time high tide on 12 December 1996.

Del Monte Beach is gently sloping with a mild tidal plateau. The slope varied between 1:45 in the surf zone to 1:12 in the swash region. Beach face topographies were generally concave-up and beach topography was relatively uniform in the alongshore direction.

Offshore root mean square wave height, H_{rms} , was 0.85 m. The average peak frequency of the incident wave spectra, \bar{F}_0 , was narrow band at 0.07 Hz ($T_p \approx 14$ s).

Changes in manometer tube water elevations were measured using differential pressure transducers fixed at the shore. The bottom mounted pressure sensors were attached to a data

logger on shore via 1/4 in armored cable. The array of manometer tubes, pressure sensors and armored cable were attached to a chain and deployed together. Data were acquired continuously at 1 Hz for the shore-fixed pressure transducers and 8 Hz for the bottom mounted pressure sensors.

The nine manometer tubes of varying lengths were used to measure variations in the mean water level relative to the farthest offshore tube. The longest tube extended 142 m from the shore-fixed pressure transducer assembly. The tubes were constructed of low density polyethylene with an inner diameter (ID) of 1/8 in. An 1/8 in ID tubing was selected to maintain a meniscus across the tubing during purging of air bubbles under pressure. Through experimentation, it was found tubes with greater than 3/16 in ID could lose the meniscus when a bubble was being pushed out over a concave curve, such as occurs over a bar, leaving an air bubble. The seaward ends of the tubes were covered with a durable filter cloth, to prevent sand from entering the tube ends.

At the shoreward end, each tube was connected to the high side (H) of a two-sided GP-50 differential pressure transducer with a range of ± 0.7 m (Figure 3). The high side of each differential pressure transducer was, in turn, connected to a common PVC reservoir located 2 m above the transducers via 3/8 in (ID) low density polyethylene tubing. This common

reservoir allowed for the air pressure inside the tubes to be identical. The low side (L) of each transducer was connected in common to the farthest offshore tube (m9), this served as a reference for the MWL.

Before each high tide, the PVC reservoir (~ 7.5 l) was filled with fresh water; in turn, a pressure pump was used to fill each of the nine polyethylene tubes to their seaward opening, purging any bubbles in the tubes. The pressure was then released and a uniform vacuum applied across all the tubes to bring the water level in each individual 3/8 in (ID) tubing to approximately 1.5 m above the transducer high side (but below the reservoir) (see Figure 3). The initial water level above the high side had to accommodate the 1 m tidal variation across high tide.

Recording by the data logger would then begin and continue until the tide progressed far enough offshore that the seaward end of the closest tube became exposed and lost its vacuum. Due to its location in the swash zone, the m1 tube opening was subject to repeated exposure to air resulting in unreliable set-up data. Problems with the m4 differential pressure transducer also prevented its use for data collection. Mechanical as well as electrical problems allowed only p3 and p7 for surface elevation data measurements.

The long, small diameter tubes act as a hydraulic filter

to high frequency waves due to viscous dampening. The head loss for steady laminar flow through a circular tube is given by (Shames 1962),

$$\frac{d\xi}{dt} = -\frac{\rho g D^2}{32 l \mu} \xi \quad (11)$$

where ξ is the head, D is the diameter of the tube, l is the tube length and μ is viscosity. The temporal variation in ξ is the change in surface elevation due to waves at the shoreward end. Solving for ξ ,

$$\xi = \xi_0 e^{-\beta t} \quad (12)$$

where ξ_0 is the initial value and β is,

$$\beta = \frac{\rho g D^2}{32 l \mu} \quad (13)$$

Equation (12) can be used to solve the response time of the manometer tube. A laboratory experiment was conducted in which a head pressure was applied to one end of an 1/8 in ID tube of length 300 m filled with fresh water. The tube was lifted 30 cm and the e-folding response time for the water to return to its original level was measured to be 39 s. Solving for t in (12) with $\beta = .010 \text{ s}^{-1}$ gives a calculated e-folding response time of 37 s for the manometer tube, showing good agreement

with the measured value. Equation (12) was also used to determine fresh water purging times for the various lengths of the nine manometer tubes. In this case, ξ is the pressure head applied by the pump to purge the tubes.

The differential pressure transducer voltage measurements were converted to sea surface elevation by a factory provided calibration curve.

Bottom pressure sensor measurements were converted to sea surface elevation by first detrending then Fourier transforming the one hour pressure record of interest, next applying the linear wave theory spectral transformation function to the complex Fourier amplitudes in the frequency domain, and finally inverse transforming to obtain a sea surface elevation time series (Guza and Thornton, 1980). At the same time, the data were band-pass filtered from 0.05 to 0.2 Hz by zeroing the Fourier coefficients outside the band, prior to inverse transforming, to remove high frequency noise and lower frequency (infragravity) waves.

Video recordings of the surf zone were obtained from a camera mounted on a 9 m high tower in the back berm region of the beach. The cross-shore distribution of the number of waves breaking at each manometer tube end was determined using the video taken during the daylight high tides. The number of waves breaking was counted manually from video pixel time

series (Lippmann and Holman, 1991). The total number of waves entering the field is found from using the surface elevation time series and the zero-up crossing method.

The bottom profile, cross-shore manometer tube end locations and relevant instrumentation elevations were surveyed on two occasions with a laser ranging theodolite and accompanying range pole. The bathymetry changed little over the two days of data collection.

B. LIP 11D LAB EXPERIMENT

Wave and mean water level data were also used from the LIP 11D Delta Flume Experiments. The flume water line is 183 m long, 5.0 m wide and water depth is maintained at 4.1 m. The sand bottom slope was 1/30 for $z > 3.7$ m and 1/20 for $z < 1.6$ m. The instrumentation used to acquire the data included an automatic sounding system, pressure sensors and a video camera. The automatic sounding system provided the alongshore bottom profile measurement in 0.5 m cross-shore increments via an echo sounder. Wave heights and mean water level were measured by ten pressure sensors mounted flush to the flume wall. The fraction of breaking waves was determined from the video camera measurements with the criteria for a breaking wave being defined as a wave crest passing a fixed point showing air-entrainment.

The flume generated random waves represented cases for a

stable, erosive, and accretive beach. The stable beach run was utilized in numeric model comparisons since its surf parameter and beach profile were similar to the Monterey Beach Experiment. The stable beach wave field was narrowband ($\bar{f}_0 = 0.2$ Hz) with $H_0 = 0.95$ m. A complete description of the LIP 11D Delta Flume Experiments is given in Roelvink and Reniers (1995).

IV. RESULTS

Sea surface elevation spectra are measured at two positions in the cross-shore for the one hour record of interest on 12 December (Figure 4). At the most offshore pressure sensor (p7) the incident waves are narrow-band swell with a peak frequency of .07 Hz. Energy at these swell frequencies decays across the surf zone due to wave breaking. At the same time the narrowband waves force infragravity waves (surf beat and edge waves) whose energy increases shoreward. The result is a shift and broadening of the wave energy spectrum to lower frequencies at pressure sensor p3.

The offshore wave forcing (S_{xx}) at the sea/swell band (0.05-0.20 Hz) is derived from the sea surface elevation time series $\eta(t)$ using,

$$S_{xx}(t) = \frac{3}{2}E_w = \frac{3}{4}\rho g \overline{[\eta(t)]^2} \quad (14)$$

where S_{xx} is averaged using a ten minute butterworth low pass filter (top panel Figure(5)). The next six panels (m2-m8), depict the mean surface elevation time series acquired by the manometer tubes. These values are a measure of the difference between the mean free surface at that location and the mean free surface elevation furthest offshore. A ten minute

butterworth low pass filter is also employed. The dashed line represents the reference (collected at m9) and for plotting purposes is assumed to be zero. The bottom box is the tidal elevation time series referenced to NGVD. All panels are compared for the same one hour of data on 12 December.

There is little phase correlation evident between the offshore forcing and the set-up.

The mean free surface at m8 suggests only slight set-down, verifying the reference tube (m9) is outside the surf zone. Largest set-down values occur at m5 located inside the maximum breakpoint as indicated by wave height transformation output (Figure 6); this agrees well with laboratory observations (Bowen et al., 1968). Largest set-up occurs at the shoreward most sensors m2 and m3.

The H_{rms} profile, calculated from equation (2), is presented in the top panel of Figure (6) for the 12 December high tide. The profile shows a good fit with the sparse measured data. The next panel shows the resulting modelled set-down/up, computed from equation (3), with and without a roller and is compared to data. The set-up model utilizing a roller shows significant improvement of data fit over the non-roller model, with the largest portion of modelled set-up occurring at the beach face. Both models under-predict set-down from the surf zone to near the shoreline. The model free

parameter values B and ψ providing the best fit were 1.45 and 2.5 respectfully.

In the flume, the set-up model utilizing a roller fits the data more closely, especially in the near-shore, with the delay in momentum transfer clearly evident (Figure 7). In this case, both roller and non-roller models over predict set-down/up. Again, the largest portion of numeric set-up with and without a roller occurs at the beach face. In the flume best fit to measured data from the model was for values of $B=0.75$ and $\psi=1.2$.

V. DISCUSSION

Differential pressure transducers with manometer tubes were effectively used to acquire continuous measurements of set-down and set-up from outside the surf zone to the nearshore. The tube closest to shore, m1, became exposed in the swash zone allowing air to enter the tube resulting in unusable data. This proved a problem for model analysis and testing as it created a data void in an area where measured and numeric set-up values diverge the most.

Purging air bubbles from the manometer tubes is essential. Air bubble formation in the exposed manometer tubes during low tide resulted in inaccurate data if left unpurged before the next data collection period (high tide). Deriving an accurate purge-time from equation (12) for each length of manometer tube to overcome tube friction and depth related pressure head proved important.

As the manometer array was quickly covered by sand, in the surf zone, it was critical to mark the tube ends with buoys for subsequent surveying. The surveyed positions provided a means for determining the percent of breakers at each tube opening utilizing video methods. Percent breakers are an important input parameter to the roller model.

The effect of including a roller in the wave

transformation model is to advect mass and momentum, resulting in the set-down shifted shoreward and set-up delayed. This gives an improved comparison with data. The cross-shore advection distances of the roller are found to depend on the steepness of the front face of the breaker (Lippmann and Thornton, 1997). The breaker angle as described by equation (10) relies on ψ . The effect of ψ on the modeled cross-shore dissipation of roller energy is shown in Figure 8 for 12 December. Also shown for comparison is non-roller energy dissipation displayed as a dashed line. Larger values of ψ indicate steeper breaker angles and shorter advection distances. Whereas smaller ψ values correspond to greater advection distances. The further a roller travels in the cross-shore, the greater the delay in momentum change, resulting in higher values of set-up at the shore.

For the Monterey Beach case the fitted ψ value is 2.5. Figure 8 shows a larger fraction of energy remaining in the roller through the cross-shore for $\psi=2.5$, allowing it to have a greater advection distance, as compared with the non-roller theory case (dashed line) which indicates local energy dissipation. This delay in momentum change explains the better fit of including the roller.

In the flume case, the optimal ψ value for the roller included set-up model was 1.2. This smaller ψ value shows much

greater advection distances for the rollers than the non-roller case. This results in momentum change closer to shore and explains the better fit to measured data in this region.

The area of the roller, and thus its advection distance, is also sensitive to the parameter B . Conceptually it would be expected $B < 1$. Previous applications of the bore dissipation model give $B > 1$ for narrowband swell cases and $B \leq 1$ for broader-band wave cases (Thornton and Guza ,1983). For cases when B is larger than unity as is found in Monterey Beach Experiment the roller advection distance is biased more by B than ψ . This is due to the roller area's cubed dependence on B being larger than its inverse dependence on ψ .

VI. CONCLUSION

Continuous measurement of set-down and set-up on a natural beach utilizing manometer tubes and differential pressure transducers has been demonstrated. The need for pressure sensors in the surf zone and the complications of accurately surveying their vertical position have been eliminated. Air intrusion in the tube closest to shore, where accurate field set-up measurements are lacking the most, can be resolved in two ways. One by using high accuracy Paroscientific pressure sensors (King 1990), or two, by putting the differential pressure transducers in a well below the watertable (Hanslow and Nielson, 1992). Air bubbles in the tubing system are avoided by purging the tubes with fresh water prior to each measurement cycle. It is important to know the time required to pump water through the tubes so that friction and pressure head can be overcome.

A set-up model incorporating roller theory is compared both with field measurements acquired from Del Monte Beach, California and flume data from Amsterdam. Roller model theory is shown to give better estimates of set-up than non-roller theory for narrow banded incident waves. The roller model still over predicts set-up in the swash region. Addition of frictional dissipation at the bottom boundary layer may

provide better results in the very shallowest water as $h \rightarrow 0$, where boundary layer effects are expected to dominate. More set-up data in this region of the cross-shore is needed.

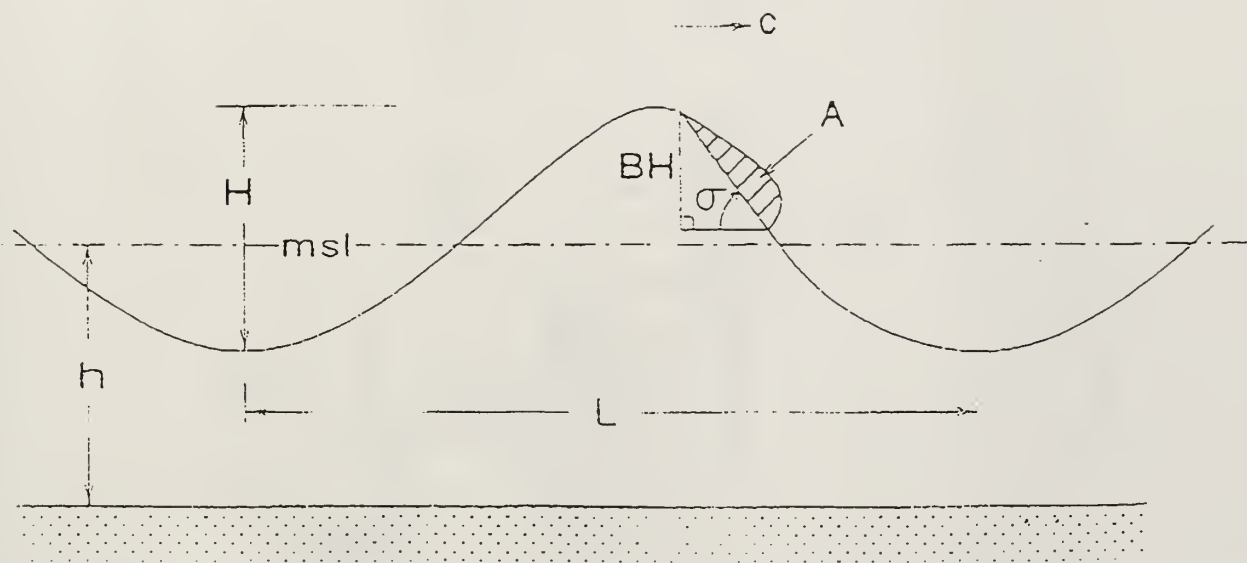


Figure 1. Schematic of wave roller geometry used in the model.

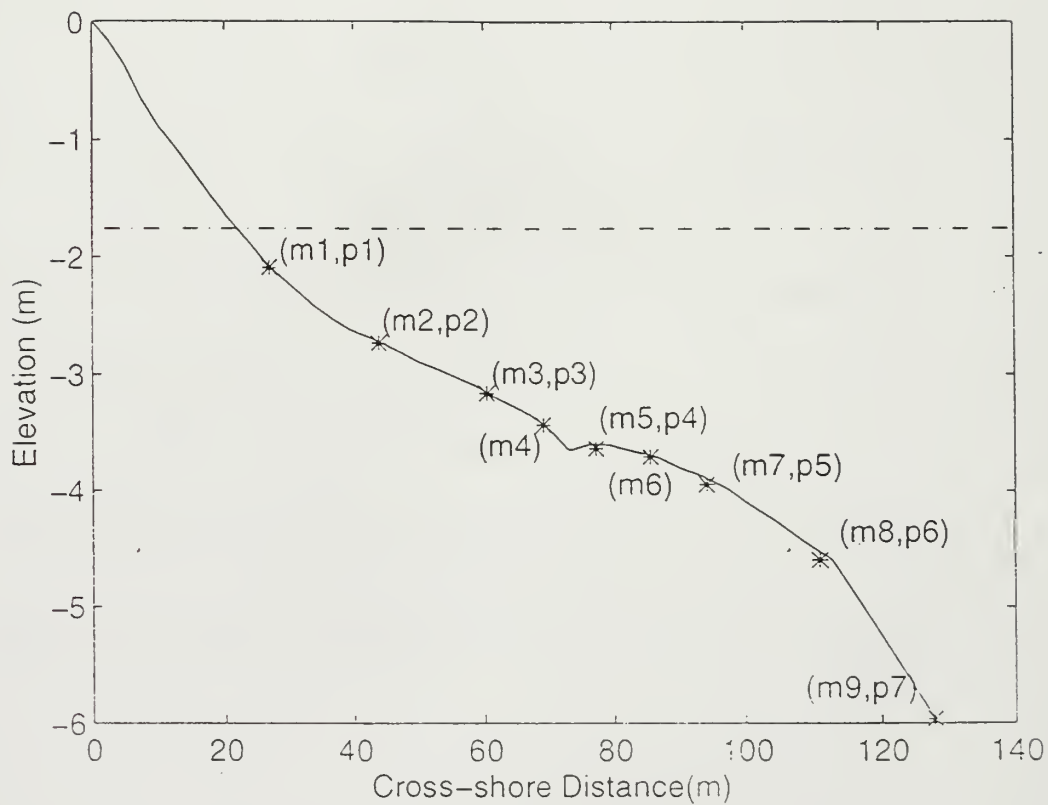


Figure 2. Beach profile for 12 December during the Monterey Beach Experiment and the location of manometer tube ends (m1-m9) and pressure sensors (p1-p7).

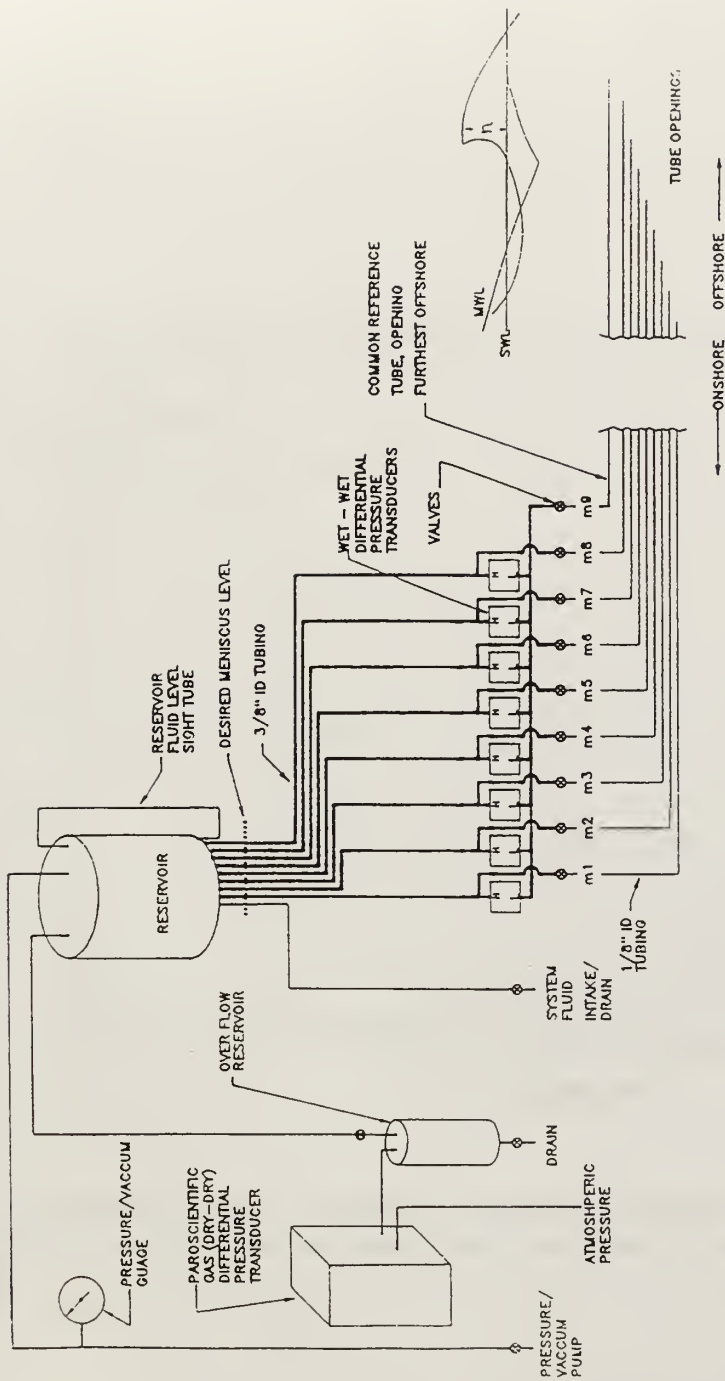


Figure 3. Set-up measurement system with onshore manometer tubes connected to high-side (H) of 2-sided differential pressure transducers. All low sides are connected in common to the farthest offshore reaching tube, m9, which acts as a reference.

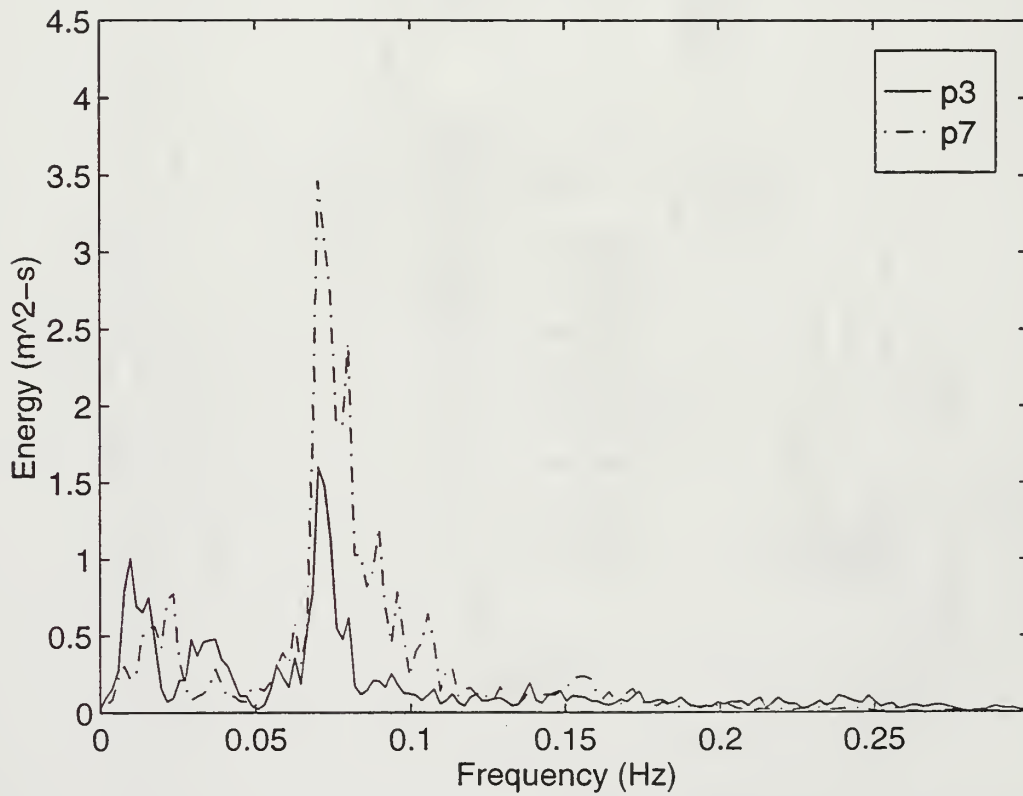


Figure 4. Sea surface elevation energy-density spectrum for 12 December at 1015 Hrs. observed at pressure sensor p3 and the most seaward sensor p7.

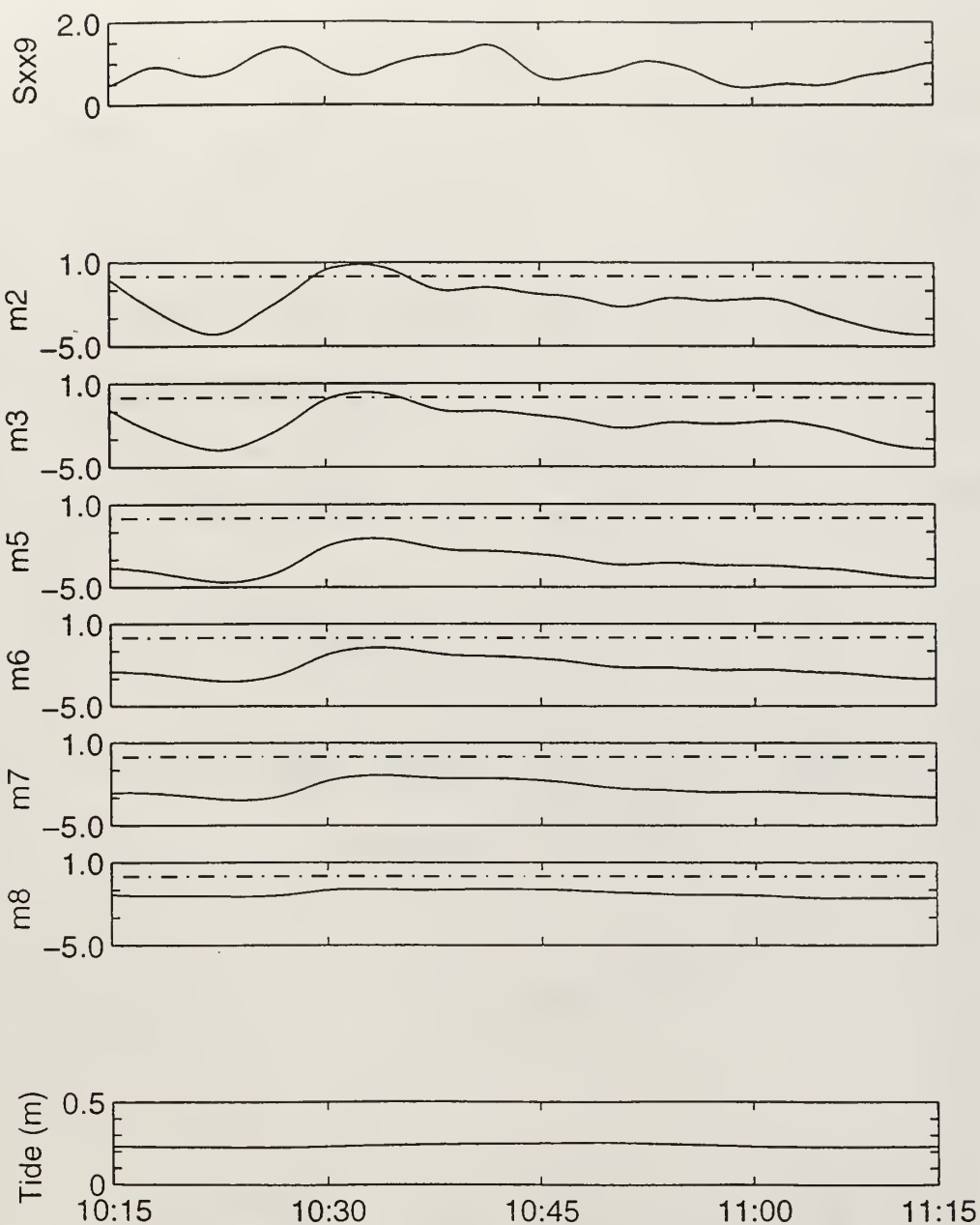


Figure 5. Top panel represents the offshore forcing, S_{xx} (J/m^2), measured at p7. The next six panels m2-m8 depict the mean surface elevation (m) time series acquired by the manometer tubes. These values are a measure of the difference between the mean surface elevation at that location and the mean surface elevation furthest offshore. The bottom panel is the tidal elevation time series.

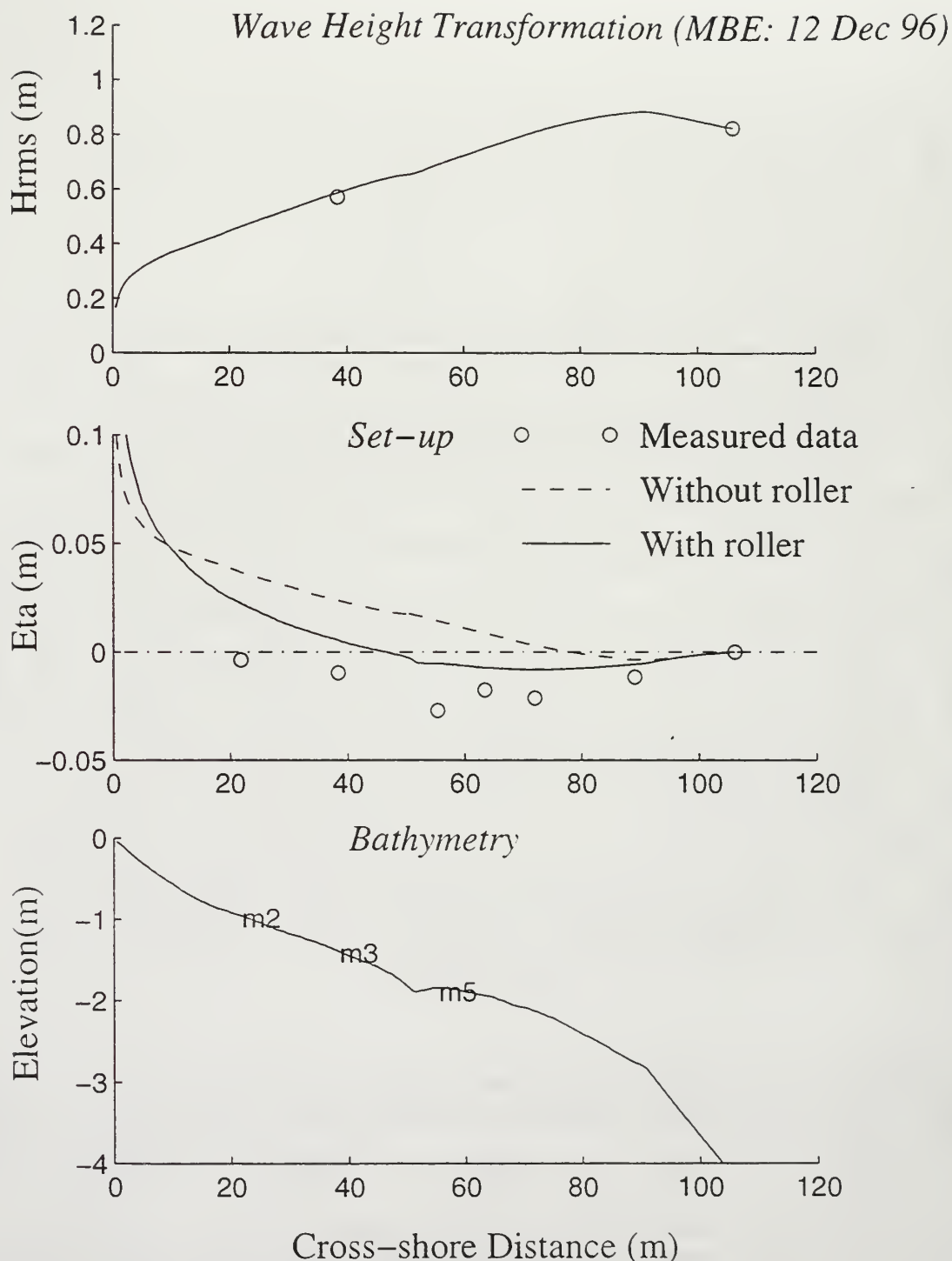


Figure 6. Top plot shows observed and predicted H_{rms} cross-shore profile for Monterey Beach Experiment. The middle plot shows predicted set-up with and without roller theory compared with observed set-up. The bathymetry is shown in the lower panel with critical manometer tube end positions for reference.

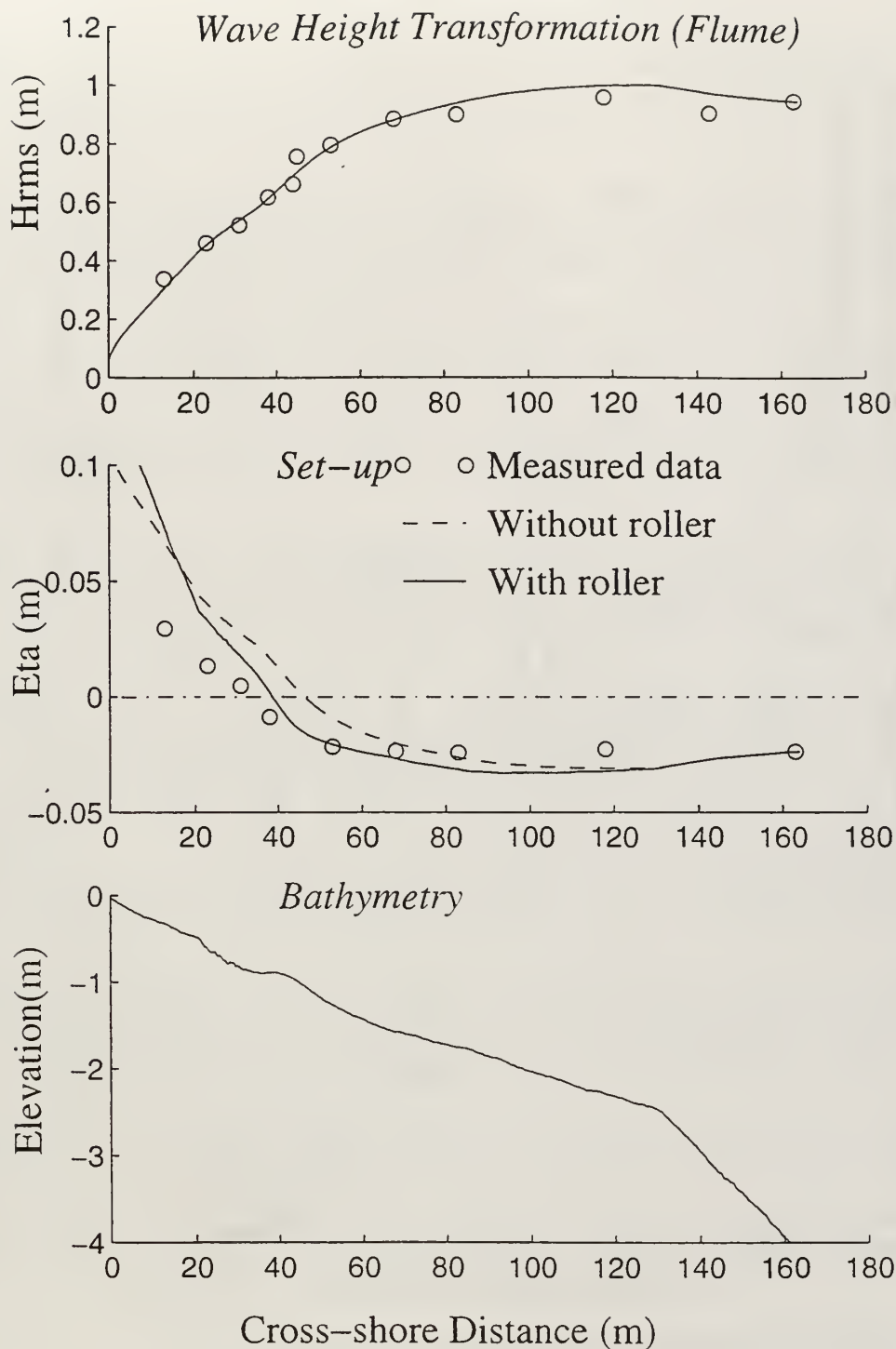


Figure 7. Same as Figure 6 for the flume measured data.

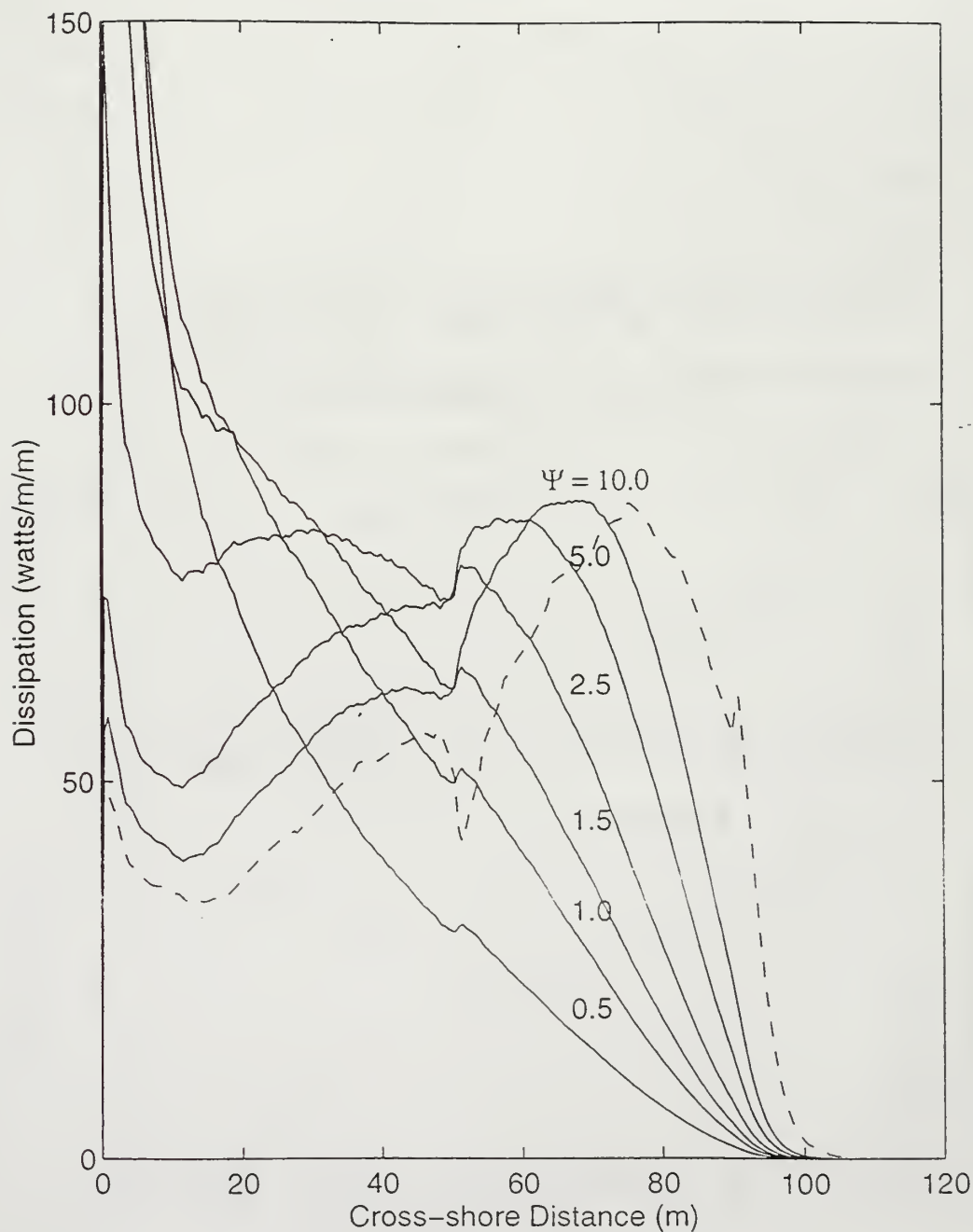


Figure 8. Modeled dissipation of roller energy plotted against cross-shore distance for a range of Ψ values (solid lines) for data obtained on 12 December. Also shown for comparison is non-roller energy dissipation (dashed line).

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